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Evidence from ice shelves for channelized meltwater flow beneath the Antarctic Ice Sheet

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Meltwater generated beneath the Antarctic Ice Sheet exerts a strong influence on the speed of ice flow, in particular for major ice streams[1,2]. The subglacial meltwater also influences ocean circulation beneath ice shelves, initiating meltwater plumes that entrain warmer ocean water and cause high rates of melting[3]. However, despite its importance, the nature of the hydrological system beneath the grounded ice sheet remains poorly characterized. Here we present evidence, from satellite and airborne remote sensing, for large channels beneath the floating Filchner–Ronne Ice Shelf in West Antarctica, which we propose provide a means for investigating the hydrological system beneath the grounded ice sheet. We observe features on the surface of the ice shelf from satellite imagery and, using radar measurements, show that they correspond with channels beneath the ice shelf. We also show that the sub-ice-shelf channels are aligned with locations where the outflow of subglacial meltwater has been predicted. This agreement indicates that the sub-ice-shelf channels are formed by meltwater plumes, initiated by subglacial water exiting the upstream grounded ice sheet in a focused (channelized) manner. The existence of a channelized hydrological system has implications for the behaviour and dynamics of ice sheets and ice shelves near the grounding lines of ice streams in Antarctica.

From extensive research in mountain glacier environments, the subglacial hydrological system has been characterized as having two potential states: distributed or channelized[4]. In a system where there is limited meltwater availability, an inefficient, low-volume, high-pressure distributed system exists. When sufficiently large amounts of meltwater are available, the system evolves into an efficient, higher volume, lower pressure channelized system. Channels may be incised into the ice or into the basal substrate. The basal velocity of an ice sheet is a function of the subglacial water depth and pressure, which is, in turn, a function of the nature of the hydrological system. Recent research in Greenland has demonstrated that similar relationships between subglacial water depth and pressure also hold true in ice-sheet settings, where even beneath multi-kilometre-depth ice, both the nature and evolution of subglacial water systems impose significant effects on ice velocity[5,6].

Channelized subglacial water flow beneath former ice sheets has previously been postulated from geomorphological evidence in Antarctica[7] and North America[8]. Subglacial lake drainage in the centre of East Antarctica has also been assumed to be channelized[9]. A key unknown, however, is whether a persistent channelized subglacial hydrological system exists widely beneath the Antarctic Ice Sheet, where water input is solely from basal melt, in the absence of surface melt. As a result, and owing to limits imposed by present ice-sheet-model resolution, existing attempts to incorporate a model of subglacial water flow into ice-sheet models have largely focused on distributed-type water flow[10].

Here we present evidence for persistent subglacial channels beneath the grounded ice sheet, derived from satellite imagery of the continent's floating ice shelves. The MODIS (Moderate Resolution Imaging Spectroradiometer) Mosaic of Antarctica imagery provides a map of surface morphology, enhancing features using a multi-image approach[11]. On some ice shelves around Antarctica, features that are distinct from standard flow stripes[12] are apparent, of the order of 1 km in width, aligned to the flow direction but occasionally migrating across the general flow direction of the ice shelf. These are particularly discernible on part of the Filchner–Ronne Ice Shelf (FRIS; Fig. 1a) but similar features also appear on the Ross Ice Shelf (RIS) and on smaller fringing ice shelves and ice tongues around Antarctica (Fig. 1b–d; see Supplementary Section S1 for imagery of all ice shelves). Here, we focus on the most striking features on the FRIS, but discuss these in the context of the wider coupled Antarctic subglacial-hydrological/ocean system.

Airborne radar measurements over the Institute Ice Stream (IIS) and Möller Ice Stream (MIS) system[13], feeding into the FRIS, cross one of the features downstream of the MIS (Fig. 2). The radar measurements reveal a sub-ice-shelf channel about 250 m in height and around 300 m wide incised upwards into the ice-shelf base. The ice-shelf surface feature is, therefore, the surface expression of a sub-ice-shelf channel, due to the lower flotation level of the thinner ice in the channel. Despite producing a surface expression, corresponding ice surface elevation measurements demonstrate that the ice is not in hydrostatic equilibrium, with bridging stresses preventing the full relaxation of the ice surface[14] (Fig. 2b).

The ice-shelf features identified correspond with the predicted exit location of subglacial meltwater beneath the grounded ice sheet[10] (Fig. 1). We propose, therefore, that the ice shelf features are a sub-ice-shelf extension of subglacial meltwater channels present beneath the grounded ice sheet. The physical mechanism for the creation of a sub-ice-shelf channel has already been described[3,15,16] as follows: subglacial meltwater reaches the grounding line of the ice sheet and, being fresh relative to the sub-shelf ocean water, rises underneath the base of the ice shelf, entraining the warmer

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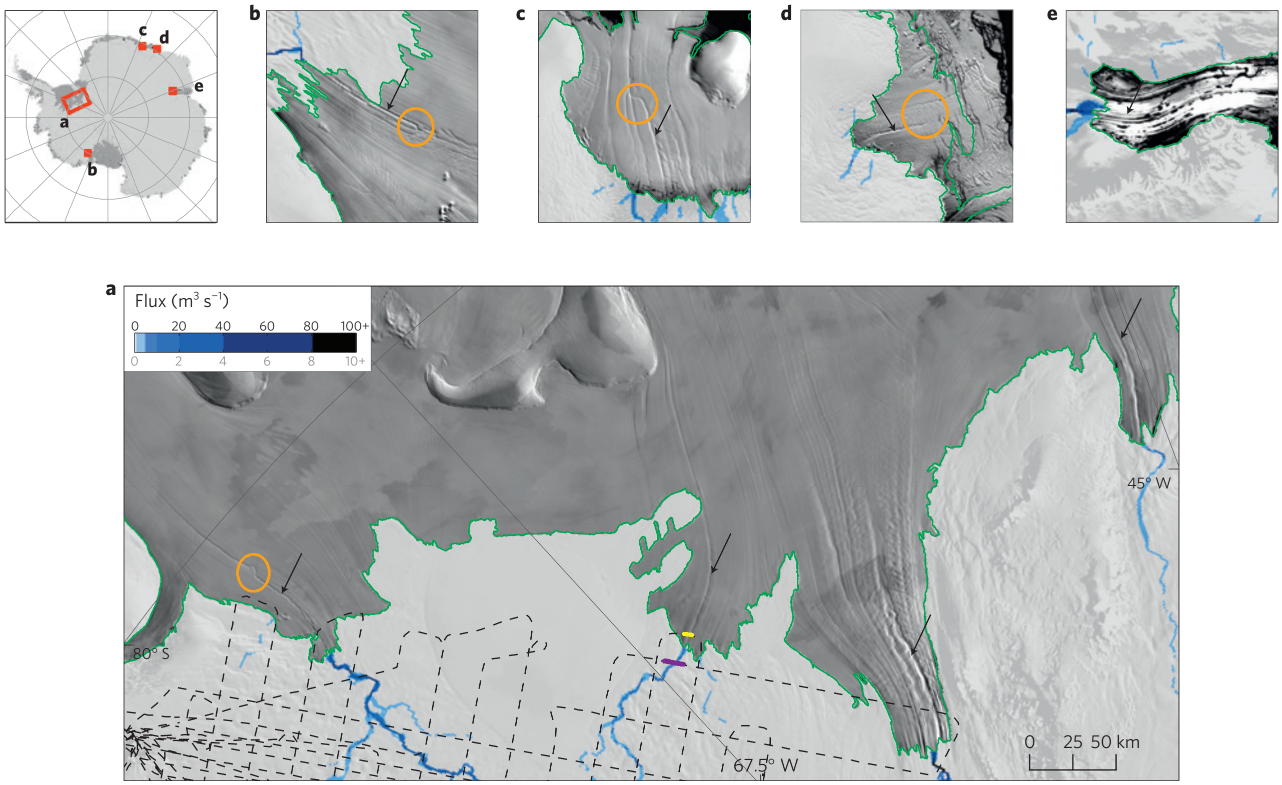

Figure 1 | Selected ice shelf features, with calculated meltwater flux beneath the grounded ice sheet overlain. a, FRIS, arrowed features are downstream of (left to right) Institute, Möller, Foundation and Support Force ice streams. **b**, MacAyeal Ice Stream (RIS). **c**,**d**, Smaller East Antarctic ice shelves. **e**, Lambert Glacier (Amery Ice Shelf). Meltwater flux colour labels in black—parts **a**,**b**,**e**, labels in grey—parts **c**,**d**. Orange circles indicate evidence of migration of the exit point of subglacial channels. The green line is the MODIS grounding line[11]. Dashed lines are airborne radar flight lines, with the yellow section indicating the part shown in Fig. 2, and purple in Supplementary Fig. S4.

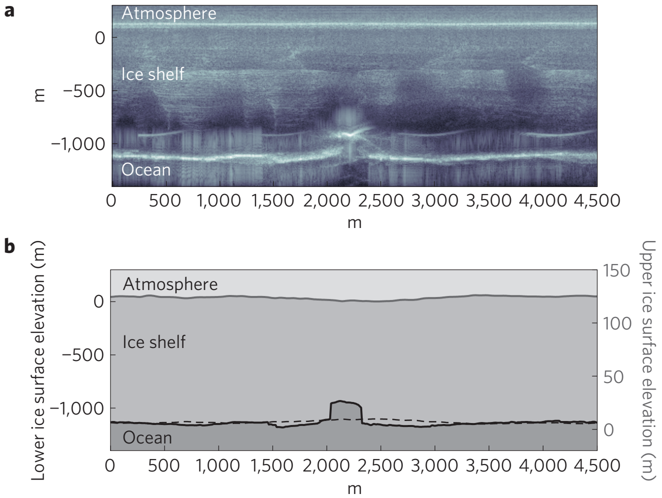

Figure 2 | Geophysical data for the Möller sub-ice-shelf channel. a, Radar echogram. **b**, Measured elevations: lower ice surface elevation picked from the radar data (solid black line), upper ice surface elevation from radar altimeter (solid grey line, note different vertical scale). The dashed line is the lower ice surface as inferred from the ice surface and a hydrostatic assumption (firn correction of 17 m). Ice flow is into the page.

ocean water as it flows (Fig. 3). This process induces large but localized sub-ice-shelf melt rates beneath the ice shelf. Once a small sub-ice-shelf channel is formed, the localized melt rates quickly enlarge it, and the meltwater plume flow is increasingly focused into this channel. Some distance downstream, the water flowing along the channel becomes supercooled, as a result of the falling pressure, and freezes, filling in the channel. This can be seen on the satellite imagery with the disappearance of the feature after several hundred kilometres (Fig. 1).

Sub-ice-shelf channels on this scale have been noted previously[17–19]. Similar channels on Petermann Glacier in Greenland were attributed to a purely oceanographic source[17], initiated by irregularities in the ice along the grounding line[16]. The mechanism proposed here to explain the FRIS features does not preclude other features having a purely oceanographic source. However, results from plume models[3,16] demonstrate that the outflow of sub-glacial meltwater at an ice shelf grounding line increases overall melt rates. The additional buoyancy associated with the sub-glacial outflow leads to a more vigorous plume and enhanced transfer of ocean heat to the ice shelf base. Subglacial outflows are thus a more effective means of initiating sub-ice-shelf plumes (and hence of creating sub-ice-shelf channels) compared with an ocean-driven plume alone. The agreement between subglacial water flow routes and sub-ice-shelf channels in Fig. 1 indicates that in this circumstance, the plume is likely to be driven by a focused subglacial water input. Elsewhere, sub-ice-shelf channels on the Amery Ice Shelf have been attributed to suture zones (shear margins) between discrete ice stream flow units[18] that feed the Lambert Glacier and join near the grounding line. However, in many cases on the FRIS, there are no distinct suture zones, and the subglacial channels are away from the shear margins, largely following the basal topography (most notably, MIS; see Supplementary Fig. S4). We can, therefore, dismiss suture zones as the cause of the ice shelf features in the FRIS region (see Supplementary Section S2 for further discussion).

Radar measurements upstream of the MIS grounding line are inconclusive about the presence of a subglacial channel under the

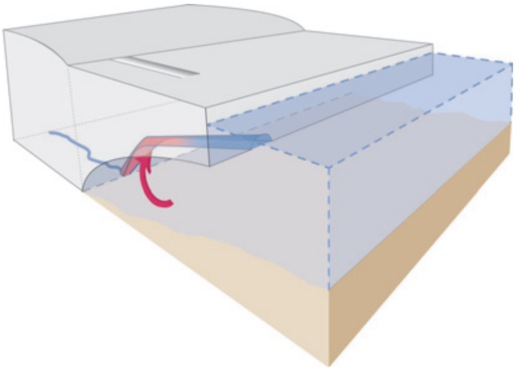

Figure 3 | Proposed mechanism of channel formation. The red arrow indicates the entrainment of relatively warm ocean water to facilitate high localized sub-ice-shelf melt rates. Not to scale.

grounded ice (Supplementary Section S3, also ref. 17), suggesting that any channel is small in comparison with the channel it feeds beneath the ice shelf. Indeed, if the channel was incised into the ice, the subglacial channel need only be a few metres wide to drain the flux (∼10 $m^3 s^{-1}$) under the pressure gradient (Supplementary Section S4) and so would not be easily imaged by radar data with an along-track spatial resolution of ∼10 m. The sub-ice-shelf channels are visible on the satellite image close to the grounding line (within ∼1 km), so this means a quick transition from a small subglacial channel (metres in width) to a large sub-ice-shelf channel (hundreds of metres in width), requiring high sub-ice-shelf melt rates. The spatially averaged melt rate required to melt the channels is of the order of 5 $m yr^{-1}$ (Supplementary Section S5) between the MIS grounding line and the radar line location (7.8 km from grounding line). Melt rates of this order have been inferred previously for this region[15,20,21].

Despite the failure of the hydrostatic assumption at the scale of the sub-ice-shelf channels, repeat surface-altimetry measurements can provide insight into whether the channels change over time, and, hence, whether the subglacial hydrological system is changing over time. Repeat measurements between 2003 and 2009 are available from the laser altimeter on board the ICESat satellite[22]. The depth of the ice-shelf-surface channels at a specific location does not change significantly over the observation period (Supplementary Figs S6–10); however, there is evidence of advection of the features with ice shelf flow (for example, Supplementary Figs S7b5, S9b5 and S10b11). The advection of changing plume pathways indicates a shift in the outflow point of the subglacial channel at the grounding line (rather than an ocean-based, plume-driven change) and, hence, a reorganization of the hydrological system. The ice shelf, therefore, records a history of the subglacial water flow outlet locations. The more linearly continuous the ice-shelf channel, the more stable the subglacial hydrological system. There is also a distinction between a slow change in the position of the outflow (for example, Fig. 1a, IIS), indicating gradual migration of the channel at the grounding line, and a switch (for example, Fig. 1b,d), indicating a change occurring upstream that alters the location of the outflow point at the grounding line. The switch in Fig. 1d occurs ∼40 km from the grounding line; with a velocity[23] of the order of 300 $m yr^{-1}$, a switch would have occurred around 130 years ago. Figure 1c indicates the gradual splitting of a single channel into three channels at the grounding line.

As mentioned above, the ice shelf features highlighted here are more prominent in our study area of the FRIS (Fig. 1a) than elsewhere on the FRIS and on the RIS (Supplementary Section S1). A question remains as to why plumes form at some grounding lines and not at others. The main influencing factors are likely to be the nature of both the ice/ocean interface and the subglacial hydrological system.

There are two factors to consider about the ice/ocean interface: the thermal driving and ice-shelf-base slope. The freezing temperature of water decreases with increasing pressure, so the potential for the ocean to melt ice (thermal driving) increases with depth. Steeper slopes impart stronger buoyancy forcing on the ice/ocean boundary layer, leading to stronger currents along the ice base, more efficient heat transfer to the ice and hence more rapid melting[3]. Ice thickness and ice-shelf-base slope across the grounding line of the IIS and MIS (those with the most prominent features), are less than other ice streams around the FRIS (∼1,200 m ice thickness for IIS/MIS compared with >1,500 m elsewhere, ice-shelf-base elevation change of 150 m over 50 km compared with >250 m over 50 km elsewhere; ref. 24), so it seems that the nature of the ice/ocean interface is not the explanation for the occurrence of the features. The existence of the ice shelf features is also not a function of subglacial meltwater flux, with predicted subglacial meltwater fluxes comparable across ice streams flowing into both the FRIS and RIS (Supplementary Figs S1–S3). Indeed, MIS has a relatively low meltwater flux, but has a prominent ice shelf feature. This indicates that it is the stability (see Supplementary Section S7 for discussion of this term) of the hydrological system that may be the critical factor for forming these features. The RIS sector ice streams are known to have an unstable hydrological system[25]. In contrast, the widespread occurrence and longer length (up to 200 km) of the sub-ice-shelf features on parts of the FRIS suggests a more stable subglacial hydrological system in this sector of the ice sheet, particularly around the IIS/MIS system. The role of subglacial lakes in either moderating or causing subglacial water flow variations could also be a contributor to the formation and persistence of the ice shelf features.

The observations presented here demonstrate the existence of a persistent channelized subglacial drainage system near the grounding line of major ice streams in Antarctica. A channelized subglacial drainage system has many impacts on how we consider and investigate the behaviour of the ice sheet. A localized input of meltwater to the cavity will have an impact on predicted sub-ice-shelf melt rates, particularly at the grounding line, which will in turn affect predictions of ice stream behaviour. The process described here also has implications for ice shelf structure; it has been shown previously that lineations of accreted marine ice can serve to stabilize ice shelves[26,27]. The nature of the hydrological input to the ocean also has implications for bulk nutrient delivery[28]. Most critically, the conventional use of distributed subglacial hydrological structures in existing numerical ice sheet models of the evolution of the Antarctic Ice Sheet fails to reflect fully the true nature of the system; greater detail is required to adequately represent the role of the hydrological system in the evolution of the ice sheet.

Methods

The subglacial water flow paths beneath the grounded ice sheet were predicted on the basis of modelled subglacial melt rates[29] and routing of the subglacial meltwater down the hydraulic potential[10,30]. The approach follows that of ref. 10, following the steady-state approach, which uses a flux routing algorithm to calculate upstream water flux for each grid cell. The subglacial water routing algorithm makes no assumption about the nature of the subglacial hydrologic system, except that the calculation of the hydraulic potential assumes that the water pressure is at the ice overburden pressure, neglecting variation in water pressure that will result from a channelized system. The hydraulic potential was calculated using the 1 km ice thickness and bed topography from the BEDMAP2 compilation[24]. The subglacial water routing algorithm is, therefore, run at a 1 km resolution, giving a broad scale indication of the flow routes and subglacial water flux, although the channel features are likely to be on a smaller scale than this.

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References

1. Stearns, L. A., Smith, B. E. & Hamilton, G. S. Increased flow speed on a large East Antarctic outlet glacier caused by subglacial floods. *Nature Geosci.* **1,** 827–831 (2008).

2. Tulaczyk, S., Kamb, W. B. & Engelhardt, H. F. Basal mechanics of Ice Stream B, West Antarctica 1. Till mechanics. *J. Geophys. Res.* **105,** 463–481 (2000).
3. Jenkins, A. Convection-driven melting near the grounding line of Ice Shelves and Tidewater Glaciers. *J. Phys. Oceanogr.* **41,** 2279–2294 (2011).
4. Hooke, R. L. *Principles of Glacier Mechanics* 2nd edn, Ch. 8, 197–251 (Cambridge Univ. Press, 2005).
5. Bartholomew, I. *et al.* Seasonal evolution of subglacial drainage and acceleration in a Greenland outlet glacier. *Nature Geosci.* **3,** 408–411 (2010).
6. Schoof, C. Ice-sheet acceleration driven by melt supply variability. *Nature* **468,** 803–806 (2010).
7. Sugden, D. E., Denton, G. H. & Marchant, D. R. Subglacial meltwater channel systems and ice sheet overriding, Asgard Range, Antarctica. *Geogr. Ann. A* **73,** 109–121 (1991).
8. Clark, P. U. & Walder, J. S. Subglacial drainage, eskers, and deforming beds beneath the Laurentide and Eurasian ice sheets. *Geol. Soc. Am. Bull.* **106,** 304–314 (1994).
9. Wingham, D. J., Siegert, M. J., Shepherd, A. & Muir, A. S. Rapid discharge connects Antarctic subglacial lakes. *Nature* **440,** 1033–1036 (2006).
10. Le Brocq, A. M., Payne, A. J., Siegert, M. J. & Alley, R. B. A subglacial water-flow model for West Antarctica. *J. Glaciol.* **55,** 879–888 (2009).
11. Scambos, T. A., Haran, T. M., Fahnestock, M. A., Painter, T. H. & Bohlander, J. MODIS-based Mosaic of Antarctica (MOA) data sets: Continent-wide surface morphology and snow grain size. *Remote Sens. Environ.* **111,** 242–257 (2007).
12. Glasser, N. F. & Gudmunsson, G. H. Longitudinal surface structures (flowstripes) on Antarctic glaciers. *Cryosphere* **6,** 383–391 (2012).
13. Ross, N. *et al.* Steep reverse bed slope at the grounding line of the Weddell Sea sector in West Antarctica. *Nature Geosci.* **5,** 393–396 (2012).
14. Vaughan, D. G. *et al.* Sub-glacial channels and fracture in the floating portion of Pine Island Glacier, Antarctica. *J. Geophys. Res.* **117,** F03012 (2012).
15. Jenkins, A. & Doake, C. S. M. Ice–ocean interaction on Ronne Ice Shelf, Antarctica. *J. Geophys. Res.* **96,** 791–813 (1991).
16. Gladish, C. V., Holland, D. M., Holland, P. R. & Price, S. F. Ice-shelf basal channels in a coupled ice/ocean model. *J. Glaciol.* **58,** 1227–1244 (2012).
17. Rignot, E. & Steffen, K. Channelized bottom melting and stability of floating ice shelves. *Geophys. Res. Lett.* **35,** L02503 (2008).
18. Fricker, H. A. *et al.* Mapping the grounding zone of the Amery Ice Shelf, East Antarctica using InSAR, MODIS and ICESat. *Antarct. Sci.* **21,** 515–532 (2009).
19. Mankoff, K. D., Jacobs, S. S., Tulaczyk, S. M. & Stammerjohn, S. E. The role of Pine Island Glacier ice shelf basal channels in deep-water upwelling, polynyas and ocean circulation in Pine Island Bay, Antarctica. *Ann. Glaciol.* **53,** 123–128 (2012).
20. Joughin, I. & Padman, L. Melting and freezing beneath Filchner-Ronne Ice Shelf, Antarctica. *Geophys. Res. Lett.* **30,** 1477 (2003).
21. Makinson, K., Holland, P. R., Jenkins, A, Nicholls, K. W. & Holland, D. M. Influence of tides on melting and freezing beneath Filchner-Ronne Ice Shelf, Antarctica. *Geophys. Res. Lett.* **38,** L06601 (2011).
22. Zwally, H. J. *et al.* GLAS/ICESat L2 Antarctic and Greenland Ice Sheet Altimetry Data version 31, 20th February 2003 to 8th April 2009 (NSICD, 2011).
23. Rignot, E., Mouginot, J. & Scheuchl, B. Ice flow of the Antarctic Ice sheet. *Science* **333,** 1427–1430 (2011).
24. Fretwell, P. *et al.* Bedmap2: Improved ice bed, surface and thickness datasets for Antarctica. *Cryosphere* **7,** 375–393 (2013).
25. Carter, S. P. & Fricker, H. A. The supply of subglacial meltwater to the grounding line of the Siple Coast, West Antarctica. *Ann. Glaciol.* **53,** 267–280 (2012).
26. Holland, P. R., Corr, H. J. F., Vaughan, D. G., Jenkins, A. & Skvarca, P. Marine ice in Larsen Ice Shelf. *Geophys. Res. Lett.* **36,** L11604 (2009).
27. Khazendar, A., Rignot, E. & Larour, E. Roles of marine ice, rheology, and fracture in the flow and stability of the Brunt/Stancomb-Wills Ice Shelf. *J. Geophys. Res.* **114,** F04007 (2009).
28. Raiswell, R., Tranter, M., Benning, L. G., Siegert, M. & De'ath, R. Contributions from glacially derived sediment to the global iron (oxyhydr)oxide cycle: Implications for iron delivery to the oceans. *Geochim. Cosmochim. Acta* **70,** 2765–2780 (2006).
29. Pattyn, F. Antarctic subglacial conditions inferred from a hybrid ice sheet/ice stream model. *Earth Planet. Sci. Lett.* **295,** 451–461 (2010).
30. Shreve, R. L. Movement of water in glaciers. *J. Glaciol.* **11,** 205–214 (1972).

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Author contributions

A.M.L.B. wrote the paper, J.A.G. processed the ICESat data, and N.R. and H.F.J.C. processed the radar data. A.J.P. and A.J. provided expertise on the nature of meltwater plumes and their interaction with the ice shelf. M.J.S., F.F., N.R., R.G.B., H.F.J.C., T.A.J., A.M.L.B. and D.M.R. were involved in the aerogeophysical survey. All authors commented on a draft of the paper.

Additional information

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Competing financial interests

The authors declare no competing financial interests.